Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Challenges of Small Modular Reactor Used Fuel Management in Canada

CNL Website:
https://www.cnl.ca/

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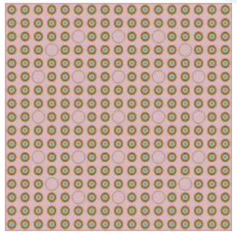
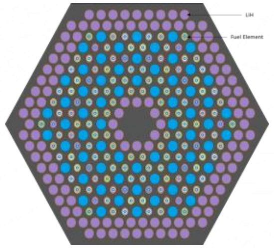
Technical Meeting on Back End of the Fuel Cycle Considerations for Small Modular Reactors
2022 September 22-23, Vienna, Austria

Challenges and Opportunities for the Different Fuel Cycle Options for SMR Designs (1/4)

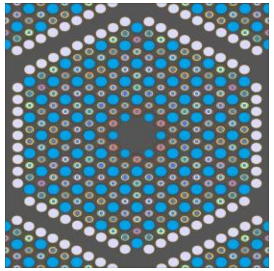
- CNL's Objective is Assist and Enable SMR Vendors and Nuclear Industry
  - Applications:
    - Smaller grid supply, remote communities, mining operations, oilsands.
  - Alignment with Government of Canada's SMR Development Roadmap and Action Plan:
    - https://smrroadmap.ca/; https://smractionplan.ca/;
  - Many vendors, many proponents.
  - Engagement with regulatory body (Canadian Nuclear Safety Commission, CNSC):
    - https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/#R2.
  - Engagement with domestic public and private electrical utilities.
    - Ontario Power Generation (OPG), Bruce Power (BP), New Brunswick Power (NBP)
    - SaskPower, Capital Power (AB), TransAlta (AB), etc.
- SMR Technologies and Issues
  - Generic/Broad-Based S&T; Technology-Specific or Design-Specific
  - Fuel cycle performance; safety characteristics.
  - Manufacturing feasibility; recycling options; proliferation concerns.
  - Long-term storage and radioactive waste disposal. Economics.

Challenges and Opportunities for the Different Fuel Cycle Options for SMR Designs (2/4)

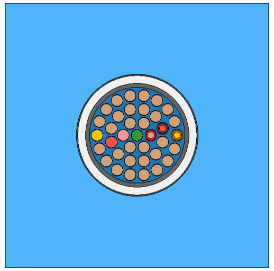




- SMR Technologies of Key Interest
  - BWRs: BWRX-300 (General Electric-Hitachi).
  - HTGRs: MMR (USNC/GFP), U-Battery, Xe-100 (X-Energy), and others.
  - PWRs: iPWR (NuScale, 50 MWe), SMR-160 (Holtec), and others.
  - MSRs: IMSR-400 (Terrestrial Energy), SSR-W300 (Moltex Energy), and others.

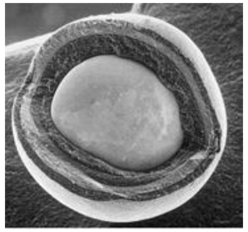


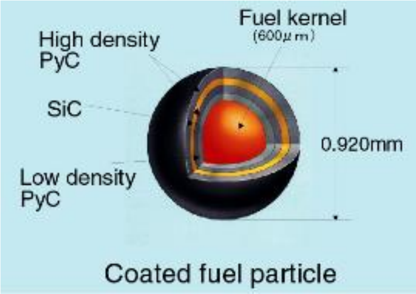
- Other SMR/AR/Gen-III+ Technologies of Potential Interest/Importance
  - SFRs: ARC-100 (ARC Canada), and others.
  - FHRs: KP-FHR-140 (Kairos Power), SmAHTR (ORNL).
  - HPRs: eVinci (Westinghouse)
  - LFRs: Sealer (LeadCold), Westinghouse, and others.
  - PT-HWRs: EC6 / CANDU-SMR
    - Well suited for recycling spent fuel and MAs from other SMRs



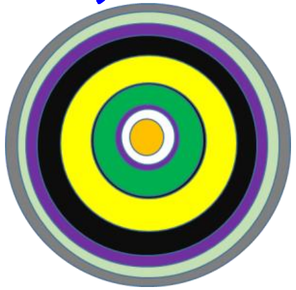
Challenges and Opportunities for the Different Fuel Cycle Options for SMR Designs (3/4)

- Advanced and Alternative Fuel Options for SMR Technologies
  - TRISO-type fuels (for HTGRs, FHRs).
  - ATF-type fuels:
    - Alternative clads, coatings; resist oxidation.
    - Fuel additives, enhanced thermal-conductivity, resist fission product transport.
  - Multi-layer, multi-clad, multi-region fuels (ATF-type, TRISO-type features).
    - Higher fissile loading density than TRISO-type fuels.
  - U, (U,Th), (Pu,Th) fuels.
    - LEU (≤5 wt% U-235/U), HALEU (19.75 wt% U-235/U).
    - Pu: recycled from LWR and HWR UNF inventories, and other sources.
  - Ceramics and metallic alloys.
    - Oxides, Oxy-carbides, Carbides, Nitrides, Silicides, Mo-alloys, Zr-alloys, etc.
  - Fluoride Salts and Chloride Salts (fuel carrier and/or coolant).
    - UF_4, ThF_4, LiF, NaF, BeF_2, ZrF_4 ; UCl_3, $PuCl_3$, NaCl



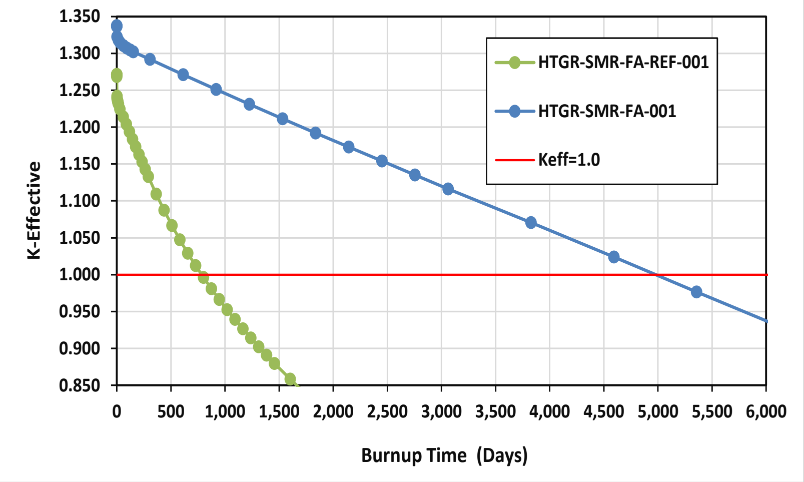


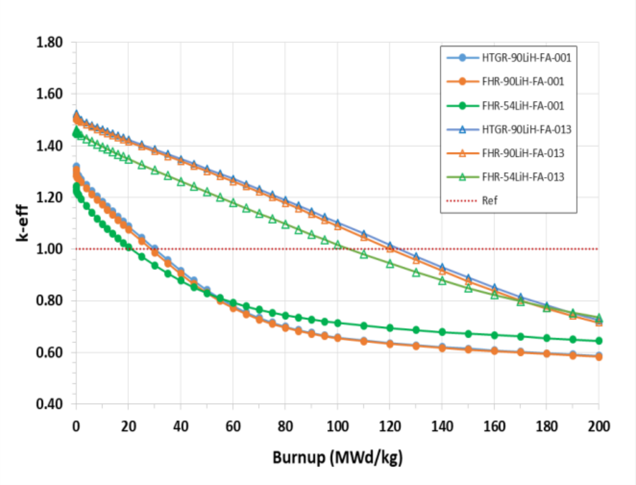
IAEA, 2019



Challenges and Opportunities for the Different Fuel Cycle Options for SMR Designs (4/4)

- Fuel Cycles of Interest / Implications
  - Very high burnup (1-batch, 3-batch, continuous refuelling).
    - Reactors for remote operations favor 1-batch refuelling
  - Once-through (for some HTGR/TRISO options).
    - Place spent fuel in retrievable long term storage / DGR.
  - Multi-stage recycling / Continuous Recycling.
    - Recycle U, Pu; Pu composition changes with each recycle.
    - Partition and separation of minor actinides (Np, Am, Cm)
    - Destruction of MA's in special fuel assemblies / fuel blocks.
    - Send fission products to DGR.
    - Consider transmutation for LLFPs (Tc-99, I-129, etc.)
  - Tandem Reactor Fuel Recycling Approaches.
    - UNF in SMRs with HALEU has high fissile content (≥ 5 wt% fiss/IHM)
    - UNF from one reactor, reprocess/refabricate and feed to other.
    - HTGR-SMR, BWR-SMR, PWR-SMR → MSR-SMR, SFR-SMR.
    - XXX-SMR → PT-HWR (high neutron economy).

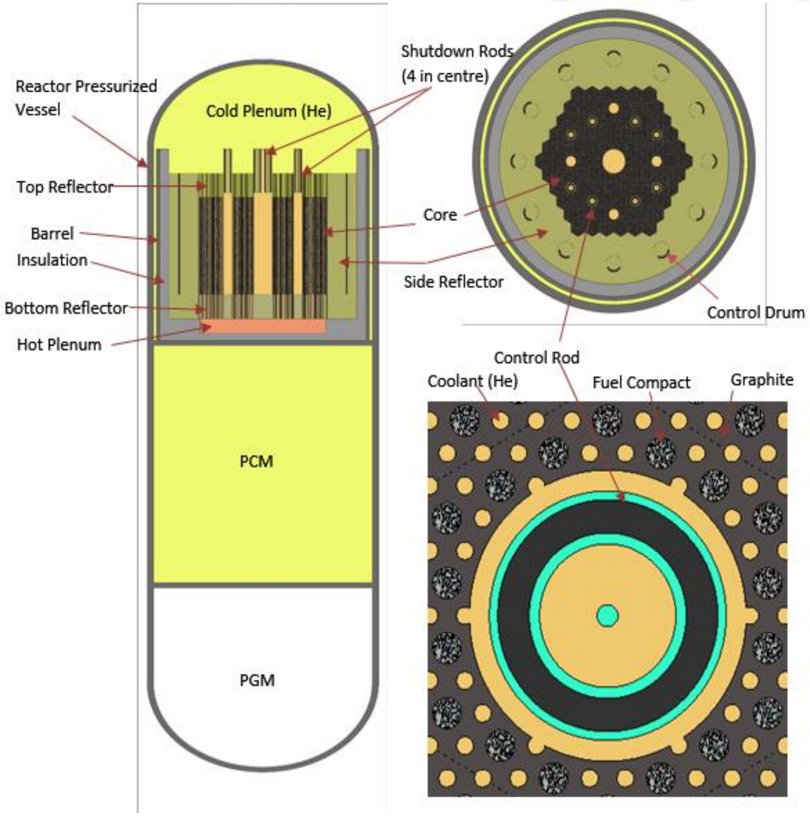


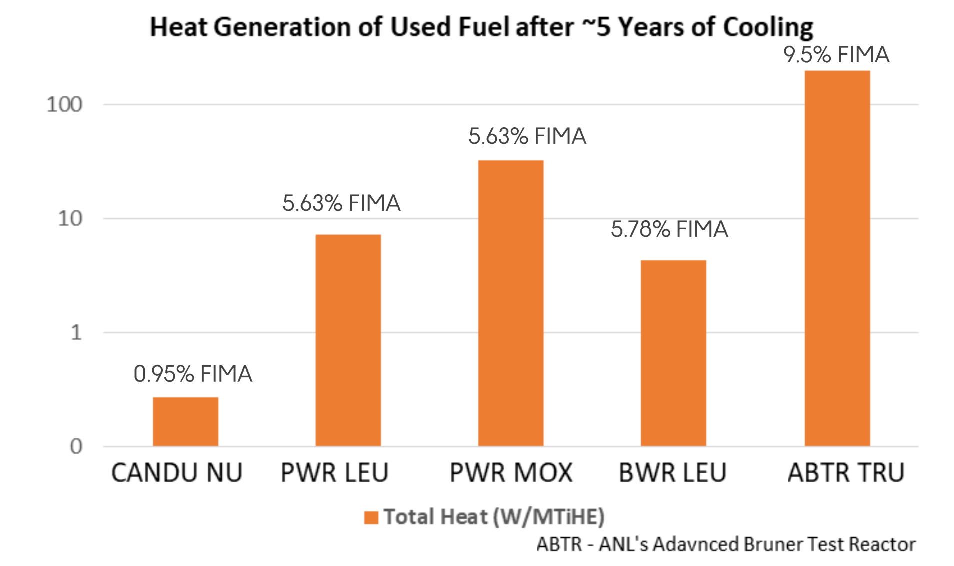


Backend Fuel Cycle (1/8)

1. SMR Used Fuel

- Used fuel inventories from SMR lifecycle usually based on a once-through fuel cycle.
  - TRISO fuel, molten salt fuel, metal fuel, oxide fuel.
  - Projected volumes, masses, material compositions for SMR designs considered in Canada.
- Radionuclides inventories and fuel depletion in used SMR fuels.
  - Computer simulation of TRISO and molten salt fuel depletion (based on generalized reactor designs).
  - Data of radionuclides inventories, heat generation, etc.





Backend Fuel Cycle (2/8)

2. SMR used fuel management options in the context of CANDU type used fuel management (I)

- Interim Storage – Current CANDU Fuel Practice:
  - Applicable to Zr-cladded oxide fuels
  - Water pool: After discharged from reactors
  - Dry storage: After 7 – 10 years, fuel bundles put in dry storage containers
- Molten salt fuels – direct dry storage (MSRE Experience)
- TRISO fuels – direct dry storage (US Virain HTGR Experience); wet & dry storage (German AVR pebbles)
- Metal fuels – wet storage, dry storage, chemical treatment for storage (EBR II experience)

Whitlock Jeremy, Splitting Atoms, Canadian Style, Deep River Science Academy and Canadian Nuclear Society, July 8th, 2010

Backend Fuel Cycle (3/8)

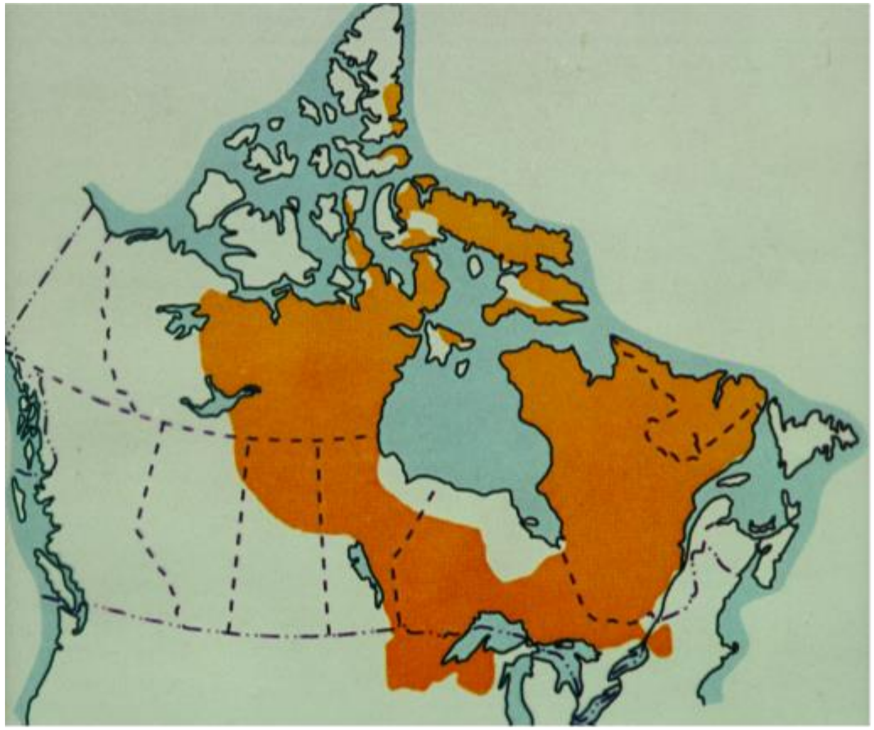
2. SMR used fuel management options in the context of CANDU type used fuel management (II)

- Transportation
  - Regulator – Canadian Nuclear Safety Commission (CNSC)
  - Regulations
    - Transport Canada's "*Transportation of Dangerous Goods Regulations*"
    - CNSC's "*Packaging and Transport of Nuclear Substances Regulations, 2015*" (PTNSR 2015) – Incorporated IAEA SSR-6 "*Regulations for the Safe Transport of Radioactive Material*"
  - Regulatory controls
    - Certification of package designs: mechanical, fire, radiation (e.g. 0.1 mSv/h at 2 m)
    - Registering users of packages
    - Licensing the transport operation of used nuclear fuel
    - Compliance inspections

Backend Fuel Cycle (4/8)

2. SMR used fuel management options in the context of CANDU type used fuel management (III)

- Long-term Storage or Disposal in a Repository - Compatibility with Adaptive Phased Management (APM) originally designed for CANDU fuels
- Pre-treatment Options
  - Packaging.
    - Without separations of non-radioactive components from used fuels.
  - Conditioning, stabilization, packaging.
    - Conditioning and stabilization after removal of non-radioactive components, as long as it is feasible and economical.
  - Reprocessing, reprocessing waste conditioning and immobilization.
    - Reprocessing for recovery of U, Pu, and minor actinides. Immobilization of fission products in glass or ceramic form.



Permanent Disposal of Used Fuel in The Canadian Shield

Whitlock Jeremy, Splitting Atoms, Canadian Style, Deep River Science Academy and Canadian Nuclear Society, July 8th, 2010

Backend Fuel Cycle (5/8)

3. Reprocessing/Recycling Implications for SMRs (I)

- Fuel types in the SMR designs.
    - SMR fuel types considered in Canada.
        - TRISO, molten salt, metal, and oxide fuels
        - Fissile elements – U, Pu, Minor Actinides (MAs)
- Reprocessing technology options.
    - Key technology options: aqueous or hydrometallurgical, pyro-electrochemical, etc.
    - Technology on shelf in Canada – DUPIC, hydrometallurgical, Th, U, and Pu reprocessing
- Waste streams, volumes, and contamination levels for reprocessing waste streams.
    - Inputs to fuel cycle economic analysis
    - Inputs to waste management strategy

Backend Fuel Cycle (6/8)

3. Reprocessing/Recycling Implications for SMRs (II)

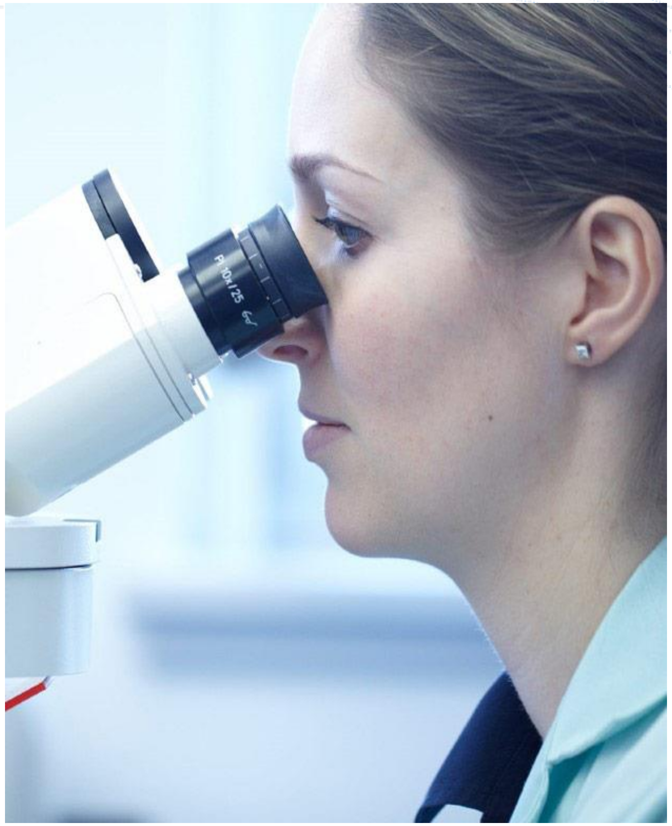
- Benefits and penalties of different reprocessing technologies.
  - Product quality: High recovery efficiencies and product purity achieved for U, Pu.
  - Waste characteristics (radiotoxicity reduction) & volumes.
  - Proliferation resistance.
  - Costs.
  - Sustainability

- Canadian Approaches
  - Interim Storage – Adaption to higher burnup fuels, e.g.; safety, security, & safeguards.
  - Transportation – Evaluation of shielding requirements and dose exposure
  - Long-term storage – Direct or after reprocessing
  - Reprocessing technology selection …

Backend Fuel Cycle (7/8)

5. Reprocessing policies in Canada

- Snap shots of the past policies:
    1. Rudimentary reprocessing from the 1940s to 1950s, not suitable for advanced fuel cycles.
    2. 1950s, in anticipation of uranium supply shortage.
    3. 1960s to 1980s, reprocessing technology for PWR, CANDU and thorium fuels. At the end of the 1980s - ceased in favor of the once-through fuel cycle - direct disposal of CANDU used fuel.
    4. 1990s, Direct Use of Spent PWR Fuel in CANDU (DUPIC) in collaboration with South Korea, supported by IAEA and US Government.



- No laws and policies that prevent reprocessing in Canada.

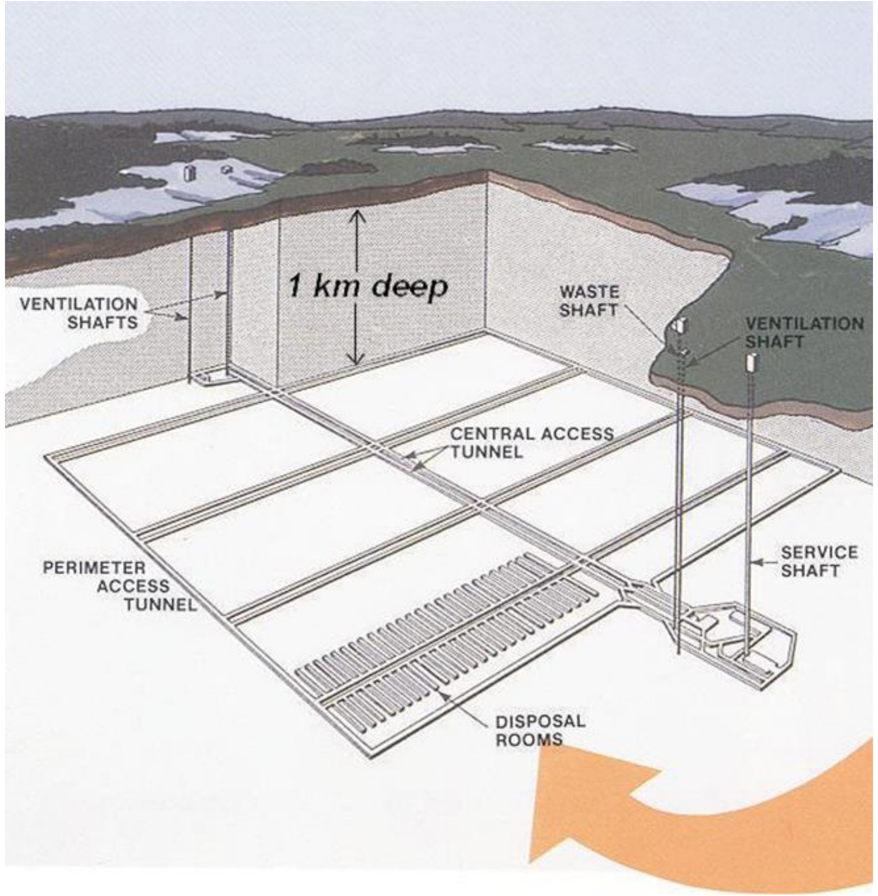
Canadian Nuclear Safety Commission regulatory framework exists to license reprocessing-like activities.

- Annual watching briefs on the development of partitioning (extended reprocessing) and transmutation (accelerators, advanced reactors) technologies by Nuclear Waste Management Organization (responsible for management and disposal of used fuel).

Backend Fuel Cycle (8/8)

6. Current backend fuel cycle & management activities supported by CNL

- Direct disposal of CANDU fuel in a DGR.
    - Radiolytic gas generation of surrounding engineering barriers and geological materials.
    - Fission product releases from used fuel with & without defects.
    - Corrosion of used fuel packaging containers, etc.
- Direct disposal of AECL research reactor fuels.
    - Stabilization and packaging of non-CANDU fuels from research reactors.
- Private sector initiatives on recovery of fissionable materials from used nuclear fuel.



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SEE BELOW FOR EXTRA SLIDES / INFORMATION

Questions?

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More info at

https://www.cnl.ca/clean-energy/small-modular-reactors/

Backend Fuel Cycle

7. Relevant activities conducted at CNL / Chalk River Laboratories

- PUREX and improvements – pure U and Pu recovery.
    - New extractants (e.g., triethylene glycol dichloride);
    - Design (e.g., a miniature plant for fuel processing);
    - Fission products separation;
    - Electrochemical techniques in aqueous processes;
    - THOREX (PUREX variant) - used Th-U-Pu fuels.
- Glass & ceramic waste forms: pioneered lab scale and pilot scale of glass & ceramic waste form.
- Notable application examples.
    - Processing of irradiated uranium target for recovery of Mo-99 for medical applications.
    - Mo-99 isotope production to be continued by private sectors.

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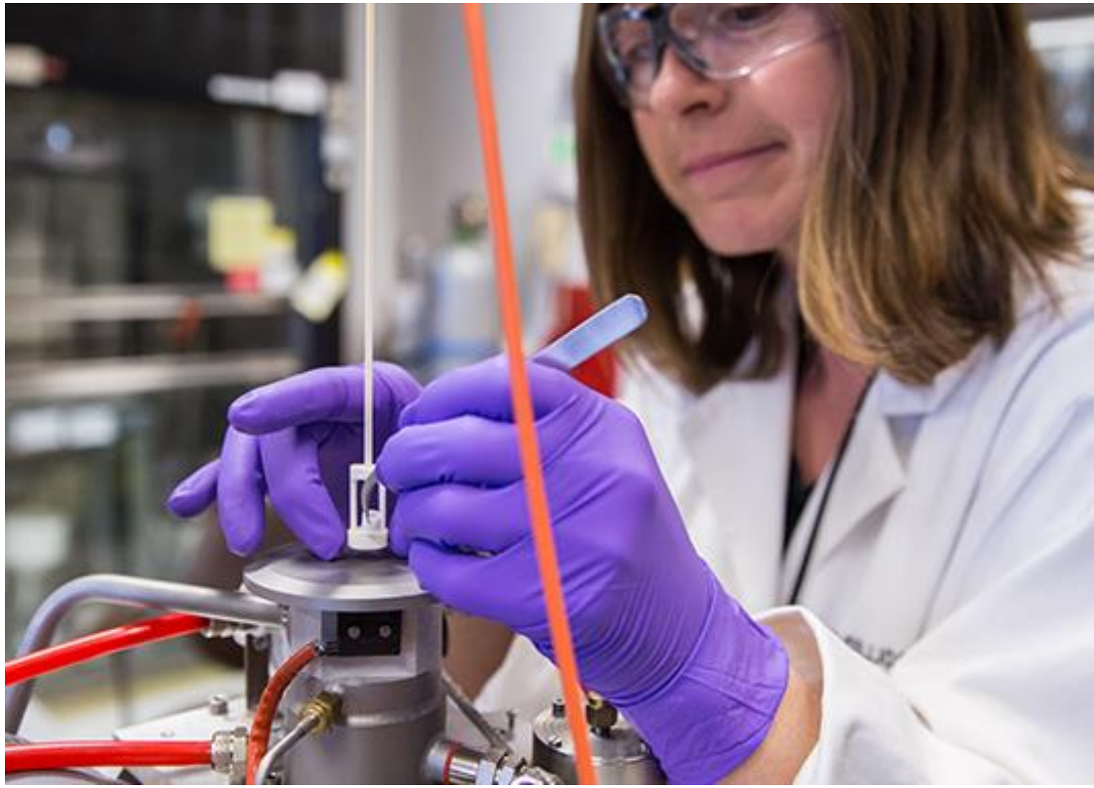
Activities by CNL on S&T in Support of Advanced Fuels and Fuel Cycles in SMR Technologies and Management of UNF

SMRs Fuel Cycles in Canada



Blair Bromley and George Sikun Xu
IAEA Consultancy Meeting on Backend Technological Options for the Fuel Cycles of SMRs
2022 March 9 - 11

Small Modular Reactors in Canada

- SMR Roadmap and Action Plan by NRCan.
- Significant to off-grid energy applications – remote communities, mining operations, etc.
- Technologies under development by private vendors.
- SMRs – Once through cycle (near term), partially or fully closed fuel cycle (long term) that would require reprocessing.
- Requirements of enriched fissile materials, such as LEU and HALEU instead of natural U.
- Technology selections influenced/driven by market pull.

CNL's Associated Laboratories and Project Sites across Canada

- Chalk River Laboratories, Ontario
- Whiteshell Laboratories, Manitoba
- Historic Waste Program, Port Hope, Ontario
- National Innovation Centre for Cybersecurity, New Brunswick
- Prototype reactors and legacy facilities

Policies and Strategies for
Managing the Back End of the Fuel Cycle for SMR Designs

- Evaluate and Assess Technology Options
  - Those of short-term interest to SMR Vendors and Nuclear Industry.
  - Those of longer-term interest and impact.

On-going Research and Development Activities to Enable Implementation of SMR Fuel Cycle Options (1/4)

- SMR-related S&T at CNL Began to Ramp up in 2015
- Several S&T Projects Relevant to SMR Fuel Cycle Development
  - Past:
    - Enablers for Advanced Fuels in Heavy Water Reactors (2015-2018)
    - An Overview of High-Level Waste from SMRs (2017-2019)
    - Improve understanding of environmental impacts and low- and intermediate-level waste streams from the operation of small modular reactors (2018-2019)
    - Improve the understanding of the environmental impacts and waste of SMR operations in support of the Pan-Canadian SMR Roadmap activities (2019-2021)
  - Current:
    - Implications on the Canadian Landscape of Advanced Non-Conventional Fuels and Fuel Cycles for SMR, Gen-IV, and Gen-III+ Technologies (2019-2022)
    - Canadian Nuclear Fuel Reprocessing and the Implications for SMR Development in Canada Definition Phase (2021-2022)

On-going Research and Development Activities to Enable Implementation of SMR Fuel Cycle Options (2/4)

- Several S&T Projects Relevant to SMR Fuel Cycle Development
  - Ongoing and Future:
    - SMR spent fuel characterization and depletion inventory for understanding of the environmental impacts and waste of SMR operations (2021-2024)
    - Canadian Nuclear Fuel Reprocessing and the Implications for SMR Development in Canada (2021-2024)
    - Economic Fuel and Fuel Cycle Sustainability and Energy Independence (2022-2026)
    - Graphite Waste Management (2022-2025)

  - **Others, including commercial, to be determined.**

On-going Research and Development Activities to Enable Implementation of SMR Fuel Cycle Options (3/4)

- Sample recent publications from CNL relevant to SMR Fuel Cycles
  - "Fuel Cycle Implications Of Deploying HTGRS In Hybrid Energy Systems As Reserve Power Generation In Ontario", *CNL Nuclear Review.* e-First https://doi.org/10.1139/CNR.2020.00002
  - "Characteristic Waste Streams from Small Modular Reactors Considered for Deployment in Canada", *Canadian Conference on Nuclear Waste Management, Decommissioning and Environmental Restoration*, Ottawa Marriott Hotel, Ottawa, ON, Canada, 2019 September 8-11. *(Published in CNL Nuclear Review)*
  - "Issues And Challenges In Assessing Ecological And Human Health Risk From The Siting of SMRs In Canada", *1st International Conference on Generation IV and Small Reactors*, Ottawa Marriott Hotel, Ottawa, ON, Canada, 2018 November 6-8. (*Published in CNL Nuclear Review)*

On-going Research and Development Activities to Enable Implementation of SMR Fuel Cycle Options (4/4)

- Sample recent publications from CNL relevant to SMR Fuel Cycles
  - "Mobile Microreactors for Deployment in Canada's North", *IAEA Technical Meeting on the Status, Design Features, Technology Challenges and Deployment Models of Microreactors*, Vienna, Austria, held virtually, 2021 April 26-29.
  - "Management of radioactive waste from application of radioactive materials and small reactors in non-nuclear industries in Canada and the implications for their new application in the future", *AIMS Environmental Science,* Accepted for publication on 2021 December 9.
  - "Inventory Calculations for Structural Materials of Small Modular Reactors (SMR)", *40th Annual Conference of the Canadian Nuclear Society and 45th Annual CNS/CNA Student Conference*, Virtual Conference, 2021 June 6–9.

Future Work at CNL

- Reprocessing & waste technology to minimize radiotoxicity in waste, reduce disposal costs, and mitigate concerns on the impact on future generations.
- Reprocessing and waste research to inform decision on technology selection, plant scale, and economics.
- Continue the work of direct fuel disposal in parallel.